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# Calibration of dial indicators using machine vision

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**Abstract**
Using automatic machine vision-based systems, the calibration of measuring instruments can be extended. With machine vision it is possible to check hundreds of points on the scale of a dial indicator, giving new insight into its sources of error.

This paper describes a machine vision-based system for the calibration of dial indicators developed at the Centre for Metrology and Accreditation in Finland, with emphasis on the calculation of measurement uncertainty.

**Keywords:** metrology, calibration, dial indicator, machine vision

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

The cost of calibration of a hand-held measuring device such as a micrometer, calliper or dial indicator is roughly equivalent to the price of a new instrument. Manual calibration therefore usually involves checking a mere 10 to 20 points. This only gives a rough figure of the precision of the instrument and is not a complete check of the scale. To reveal the sources of error for a typical dial indicator, many more points should be checked. If a dial indicator is used for quality checking on a factory production line measuring the same dimension thousands of times each year wear might occur and there would be errors at this single point on the scale of the dial indicator. If manual calibration was performed this wear would probably not be revealed and the result would be quality problems when the dial indicator gave incorrect dimensions to the part on the production line.

With automatic machine vision-based systems the calibration can be extended to several hundred points, giving a more complete picture of the errors. Developing a system of this kind is now both cheap and easy, and machine vision-based measurement systems of similar complexity have been developed in many laboratories and throughout industry. However, during development work the calculation of the uncertainty of measurement is often poorly reported. A calculation of uncertainty of measurement can be regarded as good if it complies with the guidelines given in the *Guide to the Expression of Uncertainty in Measurement* [1].

A commercially available instrument is offered by the Steinmeyer Feinmess corporation. This system is based on a video camera and a motorized length transducer. The Institute of Nuclear Energy in Bucharest has developed a laser interferometer-based instrument [2]. In this instrument the linear displacement of the dial indicator rod is measured by a Michelson interferometer. A specially designed angular transducer with phototransistors is placed over the face of the dial indicator. A vision system for calibration of a dial gauge torque wrench is also described in [3]. The problem of measuring the angle position of the pointer of a dial gauge torque wrench is similar to the measurement of the angle position of the pointer of a dial indicator.

In this particular field the authors have not found calculations of uncertainty of measurement. This paper describes a machine vision-based system, with emphasis on the calculation of measurement uncertainty. It is assumed that the reader knows the basics of the calculation of uncertainty according to [1] and is familiar with dial indicators.

## 2. The developed instrument

The operating principle is shown in figure 1. With future expansion of the instrument in mind, it was originally designed to be bigger than required for the calibration of dial indicators (figure 2). The instrument consists of a motorized stage (Physik Instrumente M 405.DG), a holder for the dial indicator

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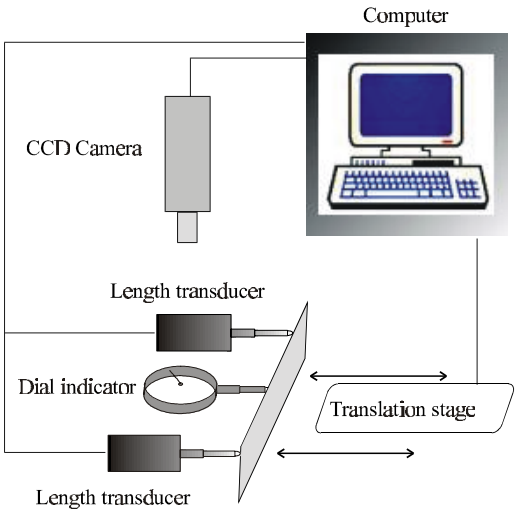


**Figure 1.** Operating principle of the instrument.

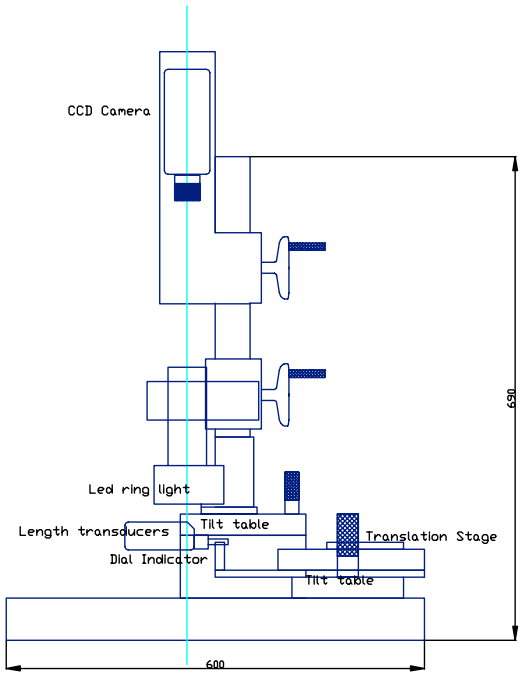


**Figure 2.** The developed instrument.

and two length transducers (Heidenhein MT25), and a height-adjustable red LED ring light (CSI FPR-100) together with a CCD camera (figure 3). A fibre ring light was also tested but reflections occurred on the glass of the dial indicator under test. The ring light has 65 LEDs, and by adjusting it to the appropriate height there are almost no shadows or glints on the dial indicator.

A CCIR standard camera (Cohu 4910) with resolution 752 × 582 was installed with a 50 mm Rainbow G50 lens. The position of the stage was measured by the two length transducers and their average used as a position reference to eliminate the Abbe error. The software was written with the Visual Basic 6 development tool in Windows NT 4 using the Matrox ActiveMIL library.

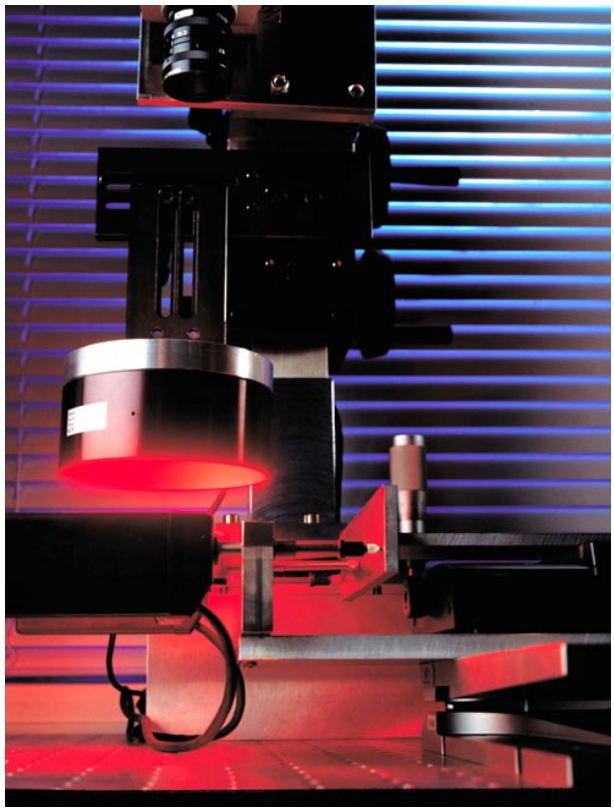

**Figure 3.** The ring light and length transducers (photo E Makkonen).

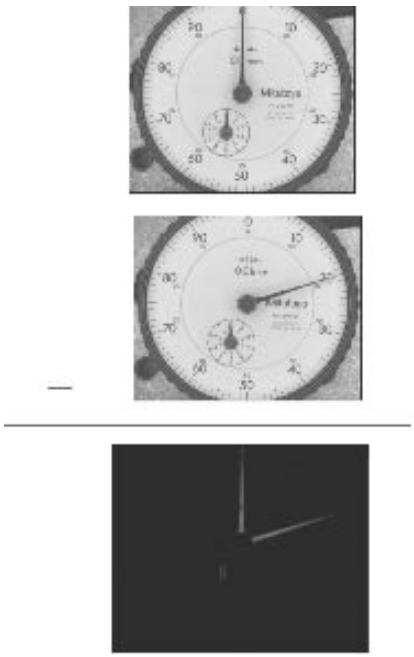

**Figure 4.** Subtraction gives a pixel by pixel difference between the images.

## 3. Image aqcuisition and segmentation

The image is digitized at the frame grabber (Matrox Meteor II) to a resolution of 768 × 576. In order to exclude unwanted features from the image a simple method also used in [3] was

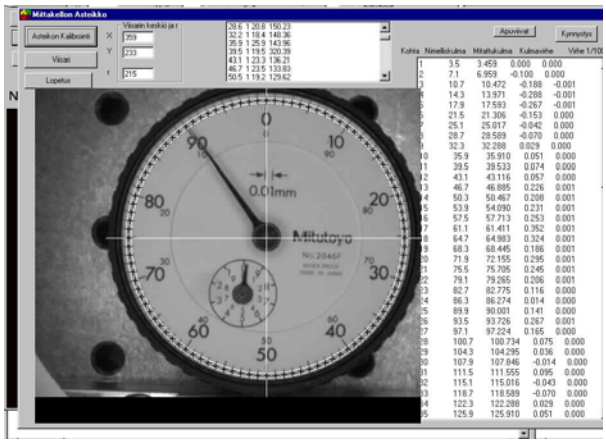

**Figure 5.** Measurement of the scale marks on the dial.

implemented. Removal of the static background comprising the dial is done by the subtraction of two images of the dial (figure 4). Since the pointers are the only moving part of the dial, subtraction results in the removal of everything in the images except the pointers [3]. The resulting image is of good quality and it was felt that thresholding would not increase the edge-finding precision. It is assumed that the large pointer is on its right lap, making it unnecessary to measure the position of the small pointer. The position of the outer part of the large pointer is found using the edge-finding functions of the MIL library. The centre of the pointer is given by the user mouse-clicking on a pair of points on the image of the dial indicator assumed to be symmetrical to the centre. The angle of the large pointer is calculated from the line crossing the assumed static centre and the established position of the outer part of the pointer. Calibration of the scale marks on the dial is also implemented in the software as a separate task (figure 5).

## 4. Results

The first test on the system was performed with an almost new Compac dial indicator with scale marks at 0.01 mm division. The error curve of the dial indicator in figure 6 shows that to get a complete picture of the errors several hundred points need to be measured. Figure 6 shows an oscillating pattern in the error curve. This frequency information can be further studied by calculating the spectrum using a Fourier transform (figure 7). In signal analysis the spectra are usually plotted as a function of frequency, but in length metrology the wavelength is more informative. The spectrum reveals harmonics at wavelengths of 0.625, 1 and 12.5 mm which possibly correspond to respective sources of error in the mechanism of the dial indicator.

## 5. Uncertainty budget

The principle of the calculation of uncertainty of measurement is described in [1] and a complete worked example for gauge blocks is described in [5]. The error sources should be evaluated from measurements, experiment, data sheets or experience. The error $\Delta L$ of a 0.01 mm division dial indicator is obtained from the relationship

$$\Delta L = L_p - \Delta L_k - L_{\text{ref}} \tag{1}$$

where $L_p$ is the measured pointer position of the dial indicator, $\Delta L_k$ is the measured error of the $k$th scale mark on the dial indicator and $L_{\text{ref}}$ is the reference position.

The pointer position $L_p$ of a 0.01 mm division dial indicator is obtained from the relationship

$$L_p = \frac{1}{2\pi} \tan^{-1}\left[\frac{x_c - x_m}{y_m - y_c}\right] + \delta L_\alpha \tag{2}$$

where $x_m$, $y_m$ is the position of the indicator tip found by

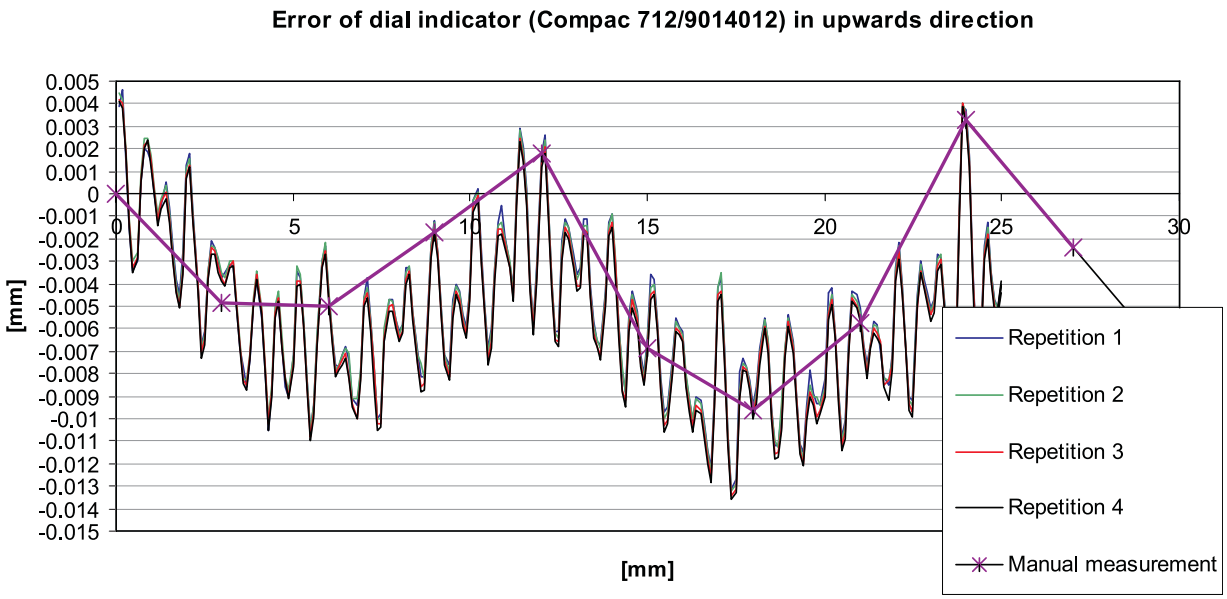


**Figure 6.** Error curve of a dial indicator measured manually and using the developed machine vision system with four repetitions.

**Table 1.** Uncertainty budget for the pointer of a 0.01 mm graduated dial indicator over a movement of 10 mm. Ideally the angle of the indicator should be 0°, but in this example the position of the indicator is found half a pixel away at 365.5, 166.

| Uncertainty component | Estimate | Standard uncertainty | Distribution | Sensitivity coeff. | Uncertainty | Degrees of freedom |
|---|---|---|---|---|---|---|
| $\delta L_\alpha$ | 0 | 1.0° | Normal | 0.01 $\mu$m/° | 0.01 $\mu$m | 8 |
| $x_c$ | 366 pixels | 0.23 pixel | Rectang. | 0.94 $\mu$m/pixel | 0.22 $\mu$m | 7 |
| $y_c$ | 311 pixels | 0.23 pixel | Rectang. | 0.94 $\mu$m/pixel | 0.22 $\mu$m | 7 |
| $x_m$ | 365.5 pixels | 0.34 pixel | Rectang. | 0.94 $\mu$m/pixel | 0.32 $\mu$m | 6 |
| $y_m$ | 116 pixels | 0.34 pixel | Rectang. | 0.94 $\mu$m/pixel | 0.32 $\mu$m | 6 |
| $L_p$ | 0.4 $\mu$m | | | | 0.55 $\mu$m | 22 |

**Table 2.** Uncertainty budget for the scale mark 0.0 mm ($k = 1$) on the dial of a 0.01 mm graduated dial indicator. Ideally the mark should be 0°, but in this example the position of the indicator is found 0.2 pixel away at 365.8, 81.

| Uncertainty component | Estimate | Standard uncertainty | Distribution | Sensitivity coeff. | Uncertainty | Degrees of freedom |
|---|---|---|---|---|---|---|
| $k$ | 1 | — — | — | — — | — | — |
| $\delta L_\alpha$ | 0 | 1.0° | Normal | 0.01 $\mu$m/° | 0.01 $\mu$m | 8 |
| $x_c$ | 366 pixels | 0.23 pixel | Rectang. | 0.66 $\mu$m/pixel | 0.15 $\mu$m | 7 |
| $y_c$ | 311 pixels | 0.23 pixel | Rectang. | 0.66 $\mu$m/pixel | 0.15 $\mu$m | 7 |
| $x_k$ | 365.8 pixels | 0.34 pixel | Rectang. | 0.66 $\mu$m/pixel | 0.22 $\mu$m | 7 |
| $y_k$ | 81 pixels | 0.34 pixel | Rectang. | 0.66 $\mu$m/pixel | 0.22 $\mu$m | 7 |
| $\Delta L_k$ | −0.1 $\mu$m | | | | 0.38 $\mu$m | 25 |

**Table 3.** Uncertainty budget for the reference position together with the mechanical error sources.

| Uncertainty component | Estimate | Standard uncertainty | Distribution | Sensitivity coeff. | Uncertainty | Degrees of freedom |
|---|---|---|---|---|---|---|
| $\delta\Delta L$ | 0 mm | 0.3 $\mu$m | Normal | 1 | 0.30 $\mu$m | 5 |
| $L_i$ | 10 mm | 0.24 $\mu$m | Rectang. | 1 | 0.24 $\mu$m | 5 |
| $\delta L_\beta$ | 0 | 0.5° | Normal | 0.04 $\mu$m/° | 0.02 $\mu$m | 8 |
| $\delta L_T$ | 0 K | 1 K | Normal | 0.12 $\mu$m/K | 0.12 $\mu$m | 5 |
| $L_{\text{ref}}$ | 10 mm | | | | 0.40 $\mu$m | 12 |

**Table 4.** Uncertainty budget for the measurement error of a 0.01 mm graduated dial indicator over a movement of 10 mm. The number of laps of the pointer are not counted and $L_{\text{ref}} = 0$ mm is used instead of 10 mm.

| Uncertainty component | Estimate | Standard uncertainty | Distribution | Sensitivity coeff. | Uncertainty | Degrees of freedom |
|---|---|---|---|---|---|---|
| $L_p$ | −0.4 $\mu$m | 0.55 $\mu$m | Normal | 1 | 0.55 $\mu$m | 22 |
| $\Delta L_k$ | 0.1 $\mu$m | 0.38 $\mu$m | Normal | 1 | 0.38 $\mu$m | 25 |
| $L_{\text{ref}}$ | 0 $\mu$m | 0.40 $\mu$m | Normal | 1 | 0.40 $\mu$m | 12 |
| $\Delta L$ | −0.4 $\mu$m | | | | 0.78 $\mu$m | 53 |

the edge finding algorithm, $x_c$, $y_c$ is the estimated centre of the indicator and $\delta L_\alpha$ are the vertical plane alignment cosine errors.

The error $\Delta L_k$ of the scale marks noted as $k = 1, 2 \ldots 100$ is obtained from the relationship

$$\Delta L_k = \frac{1}{2\pi} \tan^{-1}\left[\frac{x_c - x_k}{y_k - y_c}\right] - 0.01k + \delta L_\alpha \qquad (3)$$

where $x_k$, $y_k$ is the position of the $k$th scale mark found by the edge-finding algorithm, $x_c$, $y_c$ is the estimated centre of indicator and $\delta L_\alpha$ are the vertical plane alignment cosine errors.

The errors in the camera and lens are about ±0.3 pixel in the $x$ and $y$ directions measured with the calibration grid [4]. The standard uncertainty, assuming a rectangular distribution, is

$$\frac{0.3 \text{ pixel}}{\sqrt{3}} = 0.18 \text{ pixel}.$$

The error for the edge-finding algorithm for the pointer is estimated to be ±0.5 pixel and the standard uncertainty is

$$\frac{0.5 \text{ pixel}}{\sqrt{3}} = 0.29 \text{ pixel}.$$

Adding the camera and lens errors gives

$$\delta x_m = \delta y_m = \sqrt{0.29^2 + 0.18^2} = 0.34 \text{ pixel}.$$

To estimate the centre of the indicator it is assumed that the user gives two pairs (divisor $\sqrt{4}$) of points, each having an uncertainty of ±0.5 pixel. The standard uncertainty is

$$\frac{0.5 \text{ pixel}}{\sqrt{4}\sqrt{3}} = 0.14 \text{ pixel}.$$

Adding the camera and lens errors gives

$$\delta x_c = \delta y_c = \sqrt{0.14^2 + 0.18^2} = 0.23 \text{ pixel}.$$

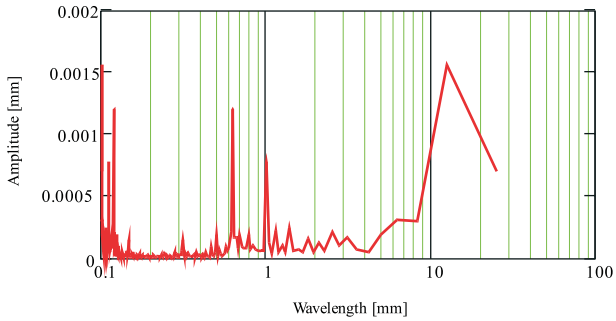


**Figure 7.** Spectrum of the error curve in figure 6 (repetition 1) as a function of wavelength.

The reference position $L_{\text{ref}}$ together with the mechanical error sources is

$$L_{\text{ref}} = L_i + \delta L_T + \delta\Delta L + \delta L_\beta \tag{4}$$

where $L_i$ is the average reading of the two length transducers used as reference, $\delta L_\beta$ are the horizontal plane alignment cosine errors, $\delta\Delta L$ is the repeatability of the dial indicator and $\delta L_T$ is the error due to thermal expansion caused by heating from the ring light.

The calibration result for the length transducers gives a $\pm 0.6$ $\mu$m uncertainty for each length transducer for a 10 mm length. The distribution of the error is assumed to be rectangular (divisor $\sqrt{3}$) and the average reading of the two transducers (divisor $\sqrt{2}$) is used. The standard uncertainty is

$$\delta L_i = \frac{0.6\ \mu\text{m}}{\sqrt{2}\sqrt{3}} = 0.24\ \mu\text{m}.$$

The standard uncertainty for alignment cosine errors is estimated to be $0.5^\circ$ for horizontal errors and $1^\circ$ for vertical errors. The vertical is interpreted as squareness between the dial indicator and the optical axis of the camera and lens. The standard uncertainty for the repeatability of a good 0.01 mm graduated dial indicator is estimated to be 0.3 $\mu$m. The standard uncertainty for warming is estimated to be 1 K which corresponds to thermal expansion of 0.12 $\mu$m for a length of 10 mm.

An example of calculation of the uncertainty for the measured error of the dial indicator at one point for each group of error sources is shown in tables 1–3. The total combined uncertainty is shown in table 4. The tables also give values for the degrees of freedom. The degrees of freedom $\nu_i$ are estimated according to the relative uncertainty in the uncertainty $\Delta u/u$:

$$\nu_i = \frac{1}{2}\left[\frac{\Delta u(x_i)}{u(x_i)}\right]^{-2}. \tag{5}$$

The degrees of freedom are combined using the Welsh–Satterthwaite formula [1]:

$$\nu_{\text{eff}} = \frac{u_c^4(y)}{\sum_{i=1}^{N} \frac{u_i^4(y)}{\nu_i}}. \tag{6}$$

To express the expanded uncertainty at the 95% confidence level the combined standard deviation (table 4) is multiplied by 2.01 ($t$-distribution for $n = 53$ and 0.95) giving $\pm 1.57$ $\mu$m.

When a dial indicator is calibrated manually, the uncertainty of the reading and interpretation of the pointer is of the same order as that obtained with the developed machine vision system.

## 6. Conclusion

Using machine vision in a normal routine calibration makes it possible to check hundreds of points on the scale of a dial indicator. This extension of the calibration gives new insight into the errors and error sources of the dial indicator. The frequency information of the error curve can also be studied by calculating the Fourier transform.

Questions of measurement error and uncertainty are often ignored. There are some natural reasons for this: if a new measurement system has been developed and it seems to work, why should anyone exceed the budget and timetable by making tests that might show that the instrument is not within the specification?

It is the view of the authors that the uncertainty budget is part of the design process for a of a measuring instrument, just like the drawings. Real confidence in a machine vision-based measuring instrument is only achieved by systematic documentation and calculation of the uncertainties as shown in this paper.

## References

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